Effects of blade sliding cutting angle and stem level on cutting energy of rice stems

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Abstract: Previous studies highlighted the significance of optimizing the cutting blade for crop harvesting and size reduction. This study investigated the effect of blade sliding cutting angle and stem level on cutting energy of single rice stem using a cutting apparatus that combined with texture analyzer. The cutting energy was determined for four blade angles. The results showed that the average cutting energy was the highest for cutting stem upper level and the lowest for cutting stem lower level. It was found that the peak cutting force per unit stem area decreased with blade sliding cutting angle increased. However, the least average cutting energy was 9.12 J/mm^2 of 45° sliding angle when cutting without counter support blade and 32.3% less than that of 60° sliding angle. When cutting with counter support blade, the cutting energy per unit stem area varied from 6.57 to 12.54 J/mm^2 as the sliding angle varied from 0° to 60°, whereas the peak cutting force per unit stem area varied from 2.46 to 0.98 N/mm^2. It was concluded that the optimal sliding cutting angle was 45° without support blade and 30° with support blade, respectively. The experiments on rice stems in this study indicated that optimization of sliding cutting angle and stem level have a significant effect on cutting energy savings. Also this study emphasized the need to further investigate the effect of the case of more moisture content and cutting speed on the cutting energy to help in selection of optimum cutting speed and harvesting time.
Keywords: texture analyzer, sliding cutting angle, size reduction, rice, cutting energy
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1 Introduction

Land management has a significant influence to match global climate change and food security with increasing world population[1]. Conservation agriculture has small disturbance to soil and cause minimum damage to the environment, so it is widely used in the world. Conservation tillage is a part of conservation agriculture, including zero tillage, reduced tillage, mulch tillage, ridge tillage and contour tillage, which is thought to be the most important aspect of conservation tillage[2]. It had positive effects on soil chemical components in the upper soil layer and contributed to the increase of wheat biomass until tillering stage compared to ploughed tillage[3,4].

As a key component of conservation tillage, the design of cutting blade has a significant effect on energy consumption and field performance of crop harvesting and size reduction equipment[5,6]. The optimum values of knife velocity, shear angle, knife approach angle and bevel were determined by experiments for cutting maize stalks, and the values were 2.65 m/s, 55°, 32° and 23°, respectively[7]. It was reported that the cutting blade oblique and cutting parameters were serious to saving energy consumption and cutting efficiency, and the results also showed that when the cut oblique angle was 60° the average energy consumption for cutting *M. x giganteus* stems was the least, approximately 7.62 J as compared to 8.73 J for 30° oblique cut and 10.07 J for straight cut[8]. Ghahraei et al.[9] carried out experiments to determine the optimum values of blade rake angle, oblique angle, blade shear angle and blade edge angle were 40°, 40°, 40°, and 25°, respectively for *Kenaf* stems. The cutting force required to cut miscanthus stems by a flat blade was 35% more than that by a serrated blade at 1.7 m/s cutting speed[10]. It was demonstrated that the blade design played an important role in the cutting force required to cut sugarcane stem, and a difference of 26% was found between the two tested designs[11]. A study which provide optimum parameters for the cutter design was conducted, and the results showed that the best combination of hemp stalk cutting was that using cutter with reciprocating double movable blades of long (120 mm) and stalk feeding speed of 0.7079 m/s and serrated-edge at cutting speed of 1.1704 m/s[12].

Size reduction is an important process of farming which is included in crop harvesting and tillage. It was reported that the blade edge sharpness, type of cutting blade, and stems' physical and mechanical properties were the major factors to affect the cutting energy of size reduction[13,14]. Studies founded that the lowest average specific cutting energy was 0.26 J/mm for a 60° oblique angle at an average cutting speed of 7.9 m/s[15]. Gupta and Oduri reported that the optimum values of tilt angle, oblique angle and blade peripheral velocity for a revolving knife-type sugarcane base cutter were 27°, 35°, and 13.8 m/s, respectively[16]. The mechanical properties of hemp stems were confirmed by laboratory experiments which were conducted using a sickle knife

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section and a counter shear, and the results showed that the blade type and interactions of stem moisture had a significant effect on resistance to penetration of hemp stem and shear strength[17]. It was suggested that cutting energy would be reduced with increase of the sliding cutting angle within a certain range, and it was appropriate to choose the sliding cutting angle between 20° and 55°[18].

Many studies investigated the effect of stems' physical and mechanical properties on cutting energy consumption[19,20]. Test was conducted to identify the corn stalk cutting process from the cutting force-displacement of corn stalks, and the results showed that corn stalks orientation had significant effect on stress, energy and mechanical cutting force, both for nodes and internodes[21]. Shinners et al.[22] expressed that the energy consumption required to shear alfalfa transversely was 10% more than longitudinal shearing. Experiments were carried out to determine the relationships among specific cutting energy of resulting particle physical properties, aperture sizes of milling screes and biomass comminution, and the results indicated that the knife mill was less energy efficient than the Retsch SK 100 hammer mill which has similarly size[23]. Galedar et al.[24] found that the accumulation of more mature fibres in the stem would contribute to more cutting energy consumed at the lower levels in the crop. Some specialized fixtures or attachments such as a Kramer shear cell or Warner-Bratzler, or specially designed knife fixtures[17,25] were either used with universal testing machine or transducers with dedicated data acquisition systems, and the study indicated that both the specific shearing energy and the shearing stress were higher in the lower region of the stem because of structural heterogeneity[26]. In order to improve the quality of mechanical crushing and returning to field of sweet potato vines, Hu Lianglong et al. studied the mechanical properties of the stems during the harvest period[27].

Thus, these literatures surveyed indicates that stems' physical and mechanical properties, cutting speed and oblique angle play a critical role in the crop stems cutting process. Zhao et al.[26] analyzed the influence of cutting speed, cutting position and parting cutter on the cutting force and consumption. The compression, shear and bending mechanical properties of dry stem were studied on a universal testing machine, and the multiple linear regression equation of mechanical index and humidity of stem was obtained[28]. Ma et al.[29] conducted experimental research on the cutting speed of rice stem under various conditions, and the main factors affecting the cutting speed and the degree of significance of the factors were found out. However, there is less study investigating the effect of sliding cutting angle on the cutting energy for rice stems. The objectives of this study were to investigate the effect of sliding cutting angle and stem level on the cutting energy of single rice stem to improve crop stems cutting process and cutting equipment.

2 Materials and methods

2.1 Specimen preparation

Rice (grown at the Huazhong Agricultural University, China) was used as the test material. The stems were cut close to the ground, collected (October 2017) and were divided equally into three levels as upper, middle and lower with equal length 100 mm of each part (Figure 1). The diameter and thickness of the stems were measured by Vernier caliper and micrometer and were recorded as shown in Table 1. The bifurcated leaves in the rice stems have withered and approached the litter state, which did not affect the experiment results. Therefore, they were removed before the experiments. The stems were weighed, oven-dried at 103°C for 24 h[24] and then weighed again to determine the moisture content. The moisture content was calculated by:

$$M=\frac{m_1-m_0}{m_1}\times 100\% \tag{1}$$

where, M is moisture content of rice stems, %; m_0 is mass of rice stems after dry, g; m_1 is mass of rice stems before drying, g.

The test was lasted for three days, and the weather was cloudy and wet, so there was no big fluctuation in moisture content of stems. The moisture content of rice stems were 82.4%±1.6%, thus, the effect of moisture content on test results could be negligible.

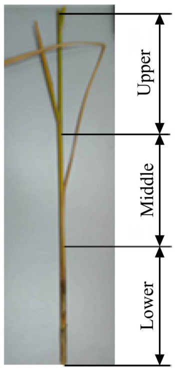


Figure 1 Test material: rice stem

Table 1 Size parameters of rice stems

Measurement	Diameter/mm			Thickness/mm		
Position	Upper	Middle	Lower	Upper	Middle	Lower
Maximum	7.22	7.69	7.62	1.80	1.92	1.82
Minimum	4.00	4.31	4.50	0.59	0.52	0.61
Average	5.30	5.79	6.06	1.12	1.10	0.96
Standard deviation	0.65	0.73	0.78	0.27	0.34	0.26
Variation coefficient	0.12	0.13	0.13	0.24	0.31	0.27

2.2 Experimental setup

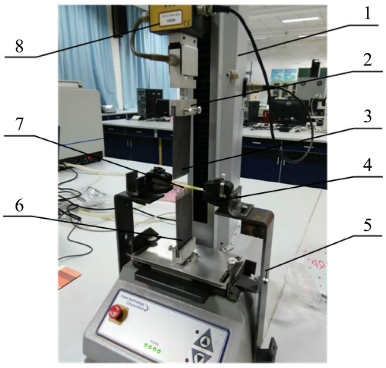
The experimental setup consisted of a texture analyzer (TMS-PRO, produced in Beijing, China) and cutting apparatus (Figure 2). The measurement range of the texture analyzer is 1000N with an accuracy of 0.01 N. There were four cutting blades with different sliding cutting angles (Figure 3). The support blade was the same as shown in Figure 3a. During the stem smashing, the blade can cut stem without supported blade under the action of high-speed rotation. However, when the rice is harvested, the blade cuts rice stem in a supported mode. Therefore, there were two types of cutting were selected for experiments, one without a support blade and the other with a support blade. The stem cutting test was performed under these two types of cutting.

During the experiment, the support blade was removed first, and the experiments were carried out at different stem level, cutting speeds and sliding cutting angles. Then, the support blade was installed, and the operation steps were similar to those of the unmounted support blade.

The two ends of the specimen were clamped and the cutting blade would cut in the middle of the stem. Before the cutting process is completed, the cutting blade moves at a constant speed. When the cutting blade contacts the stem the cutting process starts and the computer begins to record the relationship between cutting force and displacement, and shows it as a graph. The cutting energy during the stem cutting process was determined using:

$$W = \int_a^b F(s)ds \quad (2)$$

where, W is the cutting energy, J; a is the position of cutting process starts, mm; b is the position of cutting process ends, mm; $F(s)$ is the force that changes with displacement, N; s is the displacement (the difference between b and a), mm.



1. Texture analyzer 2. Blade installation 3. Cutting blade 4. Stem fixture 5. Support frame 6. Support blade 7. Stem 8. Force sensor

Figure 2 Experimental setup

a. 0° sliding cut b. 30° sliding cut c. 45° sliding cut d. 60° sliding cut

Figure 3 Cutting blade with sharp cutting edge having a single bevel angle of 30°

2.3 Cutting energy experiments

The experiment was conducted to study the effect of sliding cutting angle and stem level on the cutting energy. Refer to existing research results[17], the parameters were four sliding cutting angles (0°, 30°, 45°, and 60°, Figure 3), three stem levels (upper, middle, and lower, Figure 1), three cutting speeds (200, 350, and 500 mm/s) and two cutting types (with and without support blade). The experiment was replicated three times.

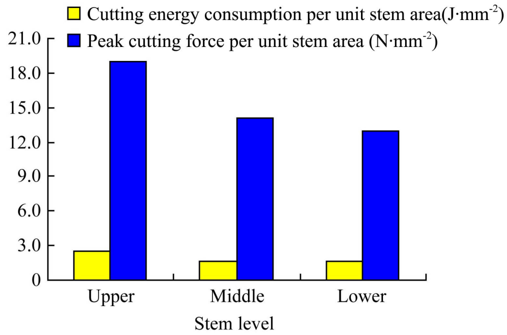
3 Results and discussion

3.1 Effect of stem level on cutting energy

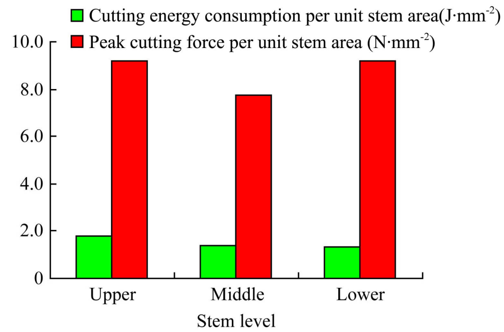
The outer diameter and wall thickness of rice stems are different, the cutting power consumption cannot be directly compared. Therefore, the cutting power consumption per unit cross-sectional area was used as a measurement index.

Figure 4a shows the effect of stem level on cutting energy without support blade. The peak cutting force per unit stem area and cutting energy per unit stem area were both the highest in cutting the upper stem level. Compare with the upper stem level, the results were similar in the middle stem level and lower stem level, and the values were 1.64, 1.66 N/mm^2 and 14.03, 12.91 J/mm^2, respectively.

Figure 4b shows the effect of stem level on cutting energy with support blade. The peak cutting force per unit stem area and cutting energy per unit stem area were smaller than that without support blade in the same test conditions. However, it was higher when cutting in the upper stem level with support blade than that with cutting in the middle and lower stem level without support blade. Overall, it may be concluded that the cutting energy would increase when cutting the upper stem level during harvesting rice. Whereas, it was not in agreement with rice stem studies[26], where the cutting energy was the minimum when cutting in the lower stem level. The test variety, growing environment and sampling method may contribute to such results.



a. Without support blade



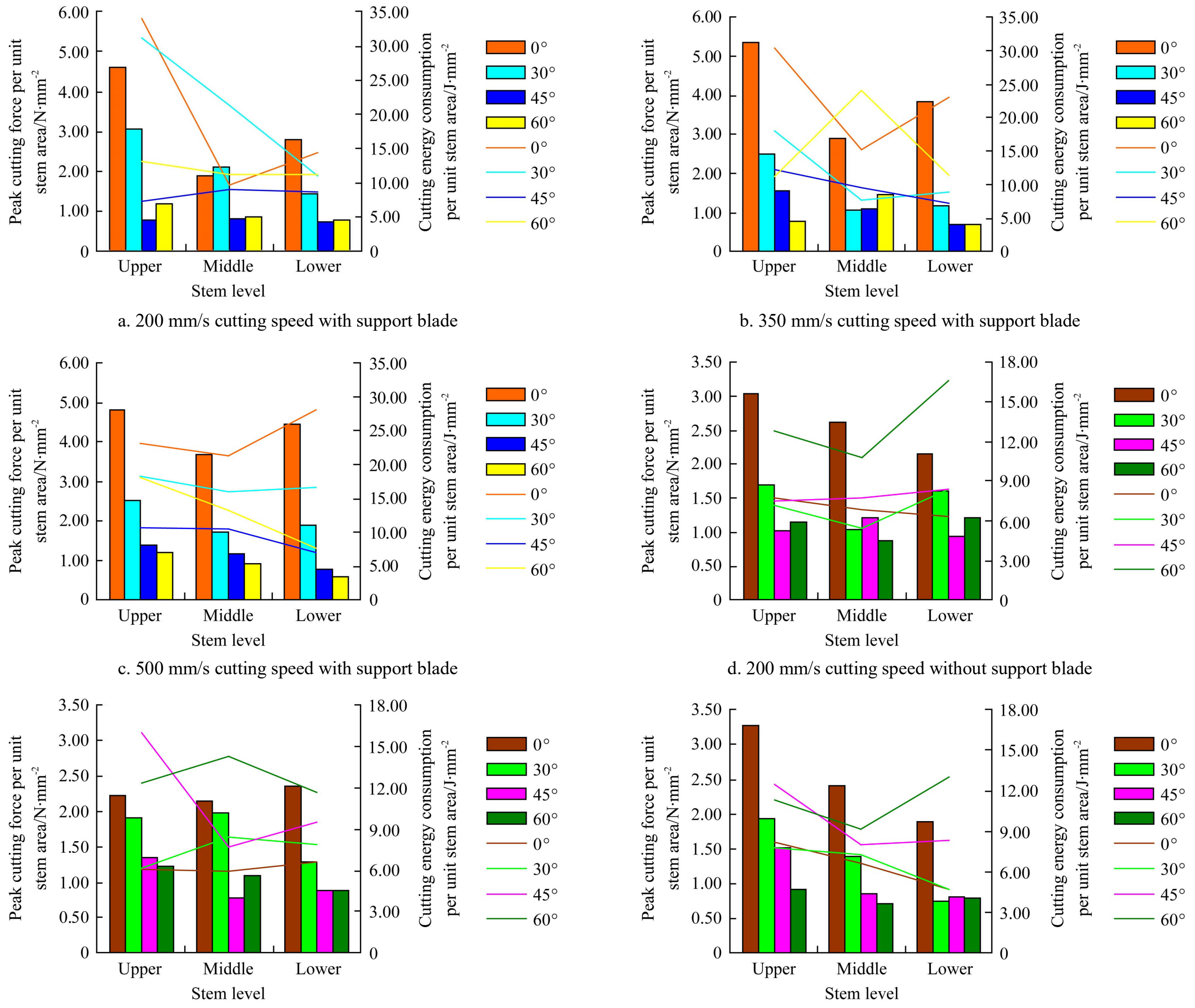
b. With support blade

Figure 4 Effects of stem levels on cutting energy per unit stem area without/with support blade

3.2 Effect of sliding cutting angle on cutting energy

Figures 5a-5c show the effect of sliding cutting angle on cutting energy without support blade, whereas Figures 5d-5f show the effect of sliding cutting angle on cutting energy with support blade. In all cases in Figure 5, the average peak cutting force per unit stem area and average cutting energy per unit stem area for 0° sliding cutting angle were much greater than that for 30°, 45° and 60° sliding cutting angle. This is in agreement with the theory of sliding cutting studies mentioned earlier[18], where the cutting force was greater with straight cut (0° sliding cut) than that with sliding cut. The peak cutting force per unit stem area decreased as the sliding cutting angle increased, however, there was no significance difference between 45° and 60° sliding cutting angle. The average peak cutting force per unit stem area were 1.03 and 0.98 N/mm^2 when the sliding cutting angle are 45° and 60°, respectively.

The trends were different between the cutting energy per unit stem area and peak cutting force per unit stem area when cutting without support blade (Figures 5a-5c). The lowest average peak cutting force per unit stem area was 0.94 N/mm^2 for 60° sliding cutting angle. For rice stems, the average peak cutting force per unit stem area varied from 3.81 to 0.94 N/mm^2 as the sliding cutting angle varied from 0° to 60°. Whereas the lowest average cutting energy per unit stem area was 9.12 J/mm^2 for 45° sliding cutting angle contrast to 22.10 J/mm^2 for 0° sliding cutting angle. Even though the peak cutting force per unit stem area for 60° sliding angle was the lowest and was 6% less than 45° sliding angle, the cutting energy per unit stem area was 32.3% higher than the latter. The results demonstrated that the optimal blade sliding cutting angle is about 45°.



a. 200 mm/s cutting speed with support blade

b. 350 mm/s cutting speed with support blade

c. 500 mm/s cutting speed with support blade

d. 200 mm/s cutting speed without support blade

e. 350 mm/s cutting speed without support blade

f. 500 mm/s cutting speed without support blade

Figure 5 Effects of different sliding cutting angles on cutting energy

Table 2 shows the comparative analysis results of sliding cutting angle without support blade. It had a significant difference in the peak cutting force per unit stem area between 30° and 45°, and between 30° and 60° at a 99% confidence level. Whereas, it has no significant difference in the peak cutting force per unit stem area between 45° and 60°. It has a significant difference in the cutting energy per unit stem area between 30° and 45° at a 95% confidence level. However, it has no significant difference in the cutting energy per unit stem area between 30° and 60°, and between 45° and 60°. The results may be noted that the sliding cutting angle has a significant effect on cutting energy when cutting without support blade.

Table 2 Comparative analysis results of sliding cutting angle without support blade

Sliding cutting angles	*p*	
	Peak cutting force per unit stem area	Cutting energy per unit stem area
30° / 45°	0.002	0.018
30° / 60°	0.001	0.643
45° / 60°	1.000	0.253

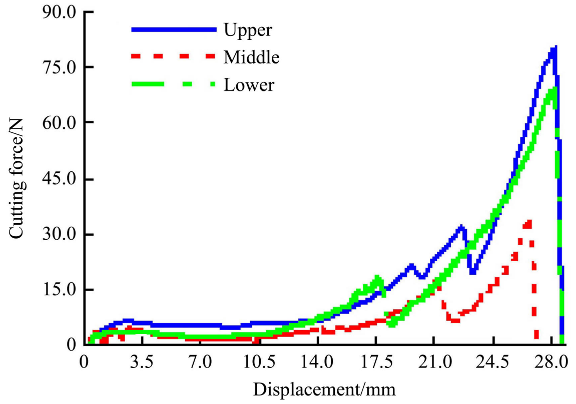
The average peak cutting force per unit stem area for 0° sliding cut when cutting with support blade was 2.46 N/mm^2, and it would decreased as the sliding cutting angle increased (Figures 5d-5f). However, the average cutting energy per unit stem area for 30° sliding cut when cutting with support blade was 7.04 J/mm^2, and it would increase as the sliding cutting angle increased. For rice stems, the cutting energy was found to vary from 6.57 to 12.45 J/mm^2 as the blade sliding angle varied from 0° to 60°. Comprehensive consideration on the cutting force per unit stem area and cutting energy per unit stem area, 30° sliding cut performed the best. It can be explained that the blade edge length increased with sliding cutting angle, the time of cutting increased so that the cutting energy increased, even though the cutting force was small.

Table 3 shows the comparative analysis results of sliding cutting angle with support blade. Similar to the cutting without support blade, it has a significant difference in the peak cutting force per unit stem area between 30° and 45°, and between 30° and 60° at a 99% confidence level. Whereas, it has no significant difference in the peak cutting force per unit stem area between 45° and 60°. It has a significant difference in the cutting energy per unit stem area between 30° and 45°, and between 45° and 60° at a 95% confidence level. Similarly, it has a significant difference in the cutting energy per unit stem area between 30° and 60° at a 99% confidence level. In conclusion, the blade sliding cutting angle has strong influence on cutting energy when cutting with support blade.

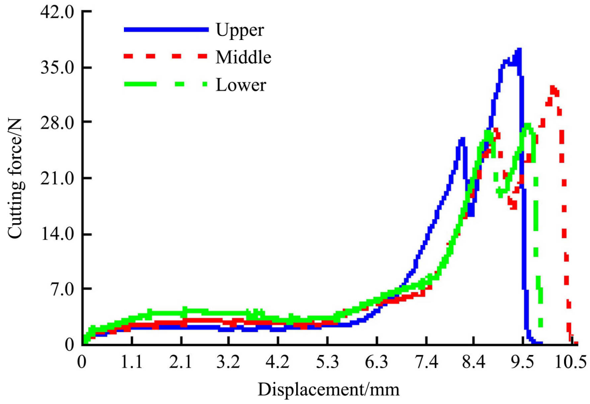
Table 3 Comparative analysis results of sliding cutting angle with support blade

Sliding cutting angles	*p*	
	Peak cutting force per unit stem area	Cutting energy per unit stem area
30° / 45°	0.007	0.032
30° / 60°	0.003	<0.0001
45° / 60°	0.704	0.013

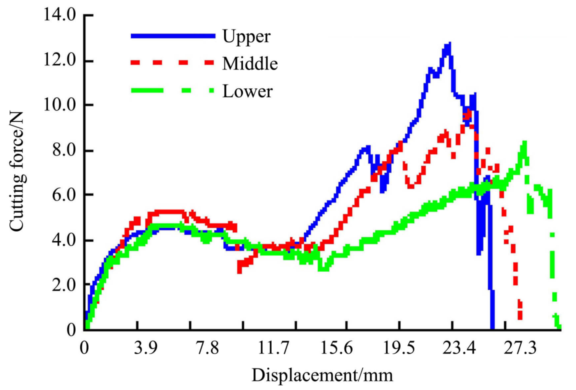
Figure 6 shows the relationships between cutting force and displacement with different sliding cutting angles (0° and 45°). The cutting process indicated that when cutting with 0° sliding cutting angle the stem was squeezed first and cut off instantaneously as it reached the peak cutting force. However, when cutting with 45° sliding cutting angle the cutting force increased first, then decreased, and then increased until cut off. The cutting force for 0° sliding cutting angle was far greater than that for 45° sliding cutting angle. When cutting with support blade, the displacement of cutting blade for 0° sliding cutting angle was longer than that for 45° sliding cutting angle. But it had no significant difference when cutting without support blade.



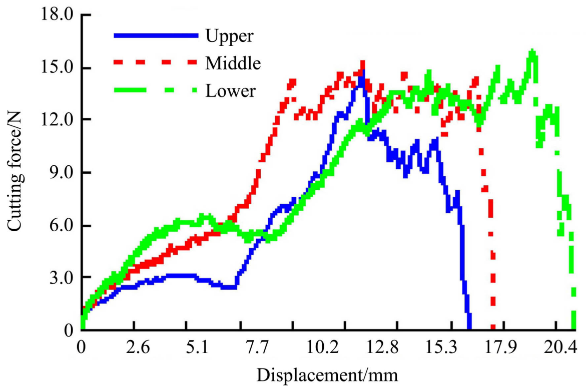
a. 0° sliding cutting angle without support blade (The stem diameters at the upper, middle and lower levels were 6.03 mm, 5.79 mm, 6.44 mm and 1.17 mm, 1.01 mm, 0.84 mm, respectively)



b. 0° sliding cutting angle with support blade (The stem diameters at the upper, middle and lower levels were 4.73 mm, 5.23 mm, 6.26 mm and 0.71 mm, 0.59 mm, 0.68 mm, respectively)



c. 45° sliding cutting angle without support blade (The stem diameters at the upper, middle and lower levels were 4.94 mm, 5.80 mm, 5.85 mm and 1.27 mm, 1.29 mm, 0.98 mm, respectively)



d. 45° sliding cutting angle with support blade (The stem diameters at the upper, middle and lower levels were 4.28 mm, 6.06 mm, 6.10 mm and 0.95 mm, 1.03 mm, 0.90 mm, respectively)

Figure 6 Relationships between cutting force and displacement with different sliding cutting angles

3.3 Effect of moisture content on cutting force and cutting energy

The moisture content of the freshly sampled rice stem was 82.4%. After the rice stems were placed for three days, the moisture content was reduced to 77.6%. After six days, the moisture content was reduced to 73.3%. The experiments were carried out at these three moisture contents.

Figure 7 shows the effect of moisture content of rice stem on peak cutting force per unit cross-section area. The peak cutting force per unit cross-section area increased as the moisture content increased.

Figure 8 shows the effect of moisture content of rice stem on cutting power consumption per unit cross-section area. The cutting power consumption per unit cross-section area also increased with the increase of moisture content of rice stems. It is because the higher the moisture content, the higher the degree of fibrosis of the plant, the greater the toughness and strength of the rice stems, and then the greater the shearing force.

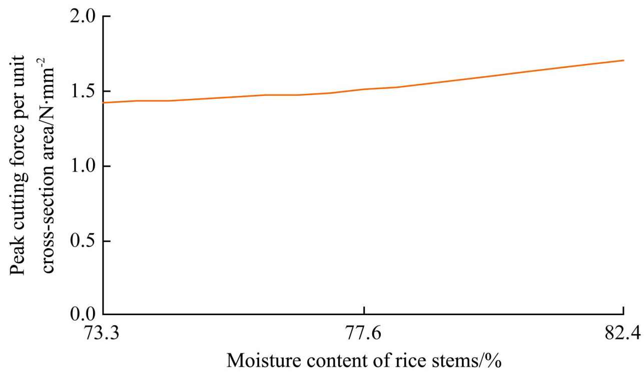


Figure 7 Effect of moisture content on peak cutting force per unit cross-section area

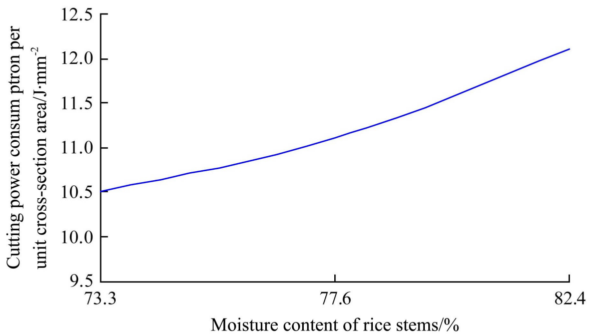


Figure 8 Effect of moisture content on cutting power consumption per unit cross-section area

4 Discussion

The structure of cutting blade, working parameters and stems' physical and mechanical properties have a significant effect on cutting energy[8,15,21,24]. Present results revealed that average peak cutting force per unit stem area and cutting energy was the highest when cutting in the upper stem level. Therefore, it may be concluded that the cutting energy would increase when cutting the upper stem level during harvesting rice. Whereas, it was not in agreement with rice stem studies[26], where the cutting energy was the minimum when cutting in the lower stem level. The test variety, growing environment and sampling method may contribute to such results.

The average peak cutting force per unit stem area for 0° sliding cutting angle was the highest. When cutting in both cutting types the peak cutting force per unit stem area decreased as the sliding cutting angle increased. This is in agreement with the theory of sliding cutting studies mentioned earlier[18], where the cutting force was greater with straight cut (0° sliding cut) than that with sliding cut. However, there was no significance difference between 45° and 60° sliding cutting angle (Tables 2 and 3). Even though the peak cutting force per unit stem area for 60° sliding angle was the lowest and was 6% less than 45° sliding angle when cutting without support blade, the cutting energy per unit stem area was 32.3% higher than the latter. The results demonstrated that the optimal blade sliding cutting angle is about 45°. Nevertheless, when cutting with support blade, comprehensive consideration on the cutting force per unit stem area and cutting energy per unit stem area, 30° sliding cutting angle performed the best. It can be explained that the blade edge length increased with sliding cutting angle, the time of cutting increased so that the cutting energy increased, even though the cutting force was small. This result is supported by reference [18].

The peak cutting force was extremely large when cutting with 0° sliding cutting angle (Figure 6), and it would cause a lot of vibration. So the corresponding equipment requires great strength such as rotary tiller. Figure 6 also demonstrated that even though the peak cutting force was small when cutting with support blade, the time of action between blade and stem increase as sliding cutting angle increase. It would led to greater friction, and consume more cutting energy. Therefore, heat treatment is necessary to increase the strength of blade such as crushing. The peak cutting force and cutting power consumption per unit cross-section area increased as the increase of moisture content of rice stem. This is consistent with the study results of the reference[28].

5 Conclusions

A cutting mechanism combined with texture analyzer was designed to investigate the energy consumption required to cut single rice stem at various blade sliding cutting angles and stem levels. The middle stem level was found to consume the lowest cutting energy per unit stem area. This can provide a reference for the selection of the height of the header when harvesting rice. It is evident that by selecting an optimal stem level, the cutting energy could be reduced during harvesting. The results of the effect of moisture content on cutting force and cutting power consumption can guide workers to choose a suitable harvest time. For 45° sliding cut without support blade, the energy per unit stem area required to cut rice stems was the least. Similarly, the energy consumption per unit stem area was the minimum when used the 30° sliding angle blade and support blade to cut rice stems. These results showed that optimization of stem level and blade sliding cutting angle will result in significant savings in cutting energy, and the optimal blade sliding cutting angles were about 45° and 30° when cutting without and with support blade, respectively. It can provide some reference for the selection of cutting mode and structure design of blade. This study emphasized the need to further investigate the effect of and high cutting speed and the case of more moisture content on the cutting energy. Further studies would help in optimization of cutting speed and selection of harvesting time.

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